Wireless Microsensors System for Monitoring Deep Subsurface Operations

DE-FE0031850

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U.S. Department of Energy

National Energy Technology Laboratory

Carbon Management and Oil and Gas Research Project Review Meeting – Carbon Storage

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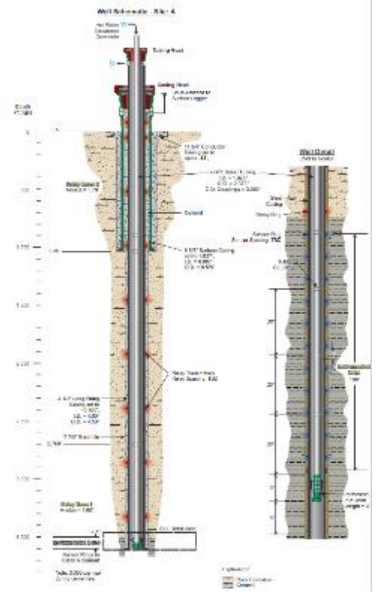

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Technical Status

- 3-year DOE-NETL project under *FOA1998 "Transformational Sensing Systems for Monitoring the Deep Subsurface" (started Feb. 2020)*
- Project Objective = Develop a technology for wireless downhole monitoring of subsurface CO_2 storage via a three-prong approach:

Feb 2020-Aug 2022

1. **Wireless MicroSensor System Development-** design and fabricate a fully integrated wireless microsensor-based downhole sensing system to **measure temperature** as the primary indicator of CO_2 presence.
2. **Field Deployment/Demonstration-** demonstrate system operational feasibility by deploying & testing the sensor system in the casing annulus of two legacy oil & gas wells in Eastern Ohio.
3. **Techno-Economic Analysis**- establish the technical feasibility & practical utility of the sensing system for reservoir/above zone monitoring in a commercial-scale CO_2 storage complex with numerical multi-phase thermal reservoir simulations and a techno-economic evaluation that benchmarks the total costs, risks and unique benefits.

Result= real time, wireless autonomous monitoring system for accurately tracking/modelling the subsurface movement of CO_2 plumes.

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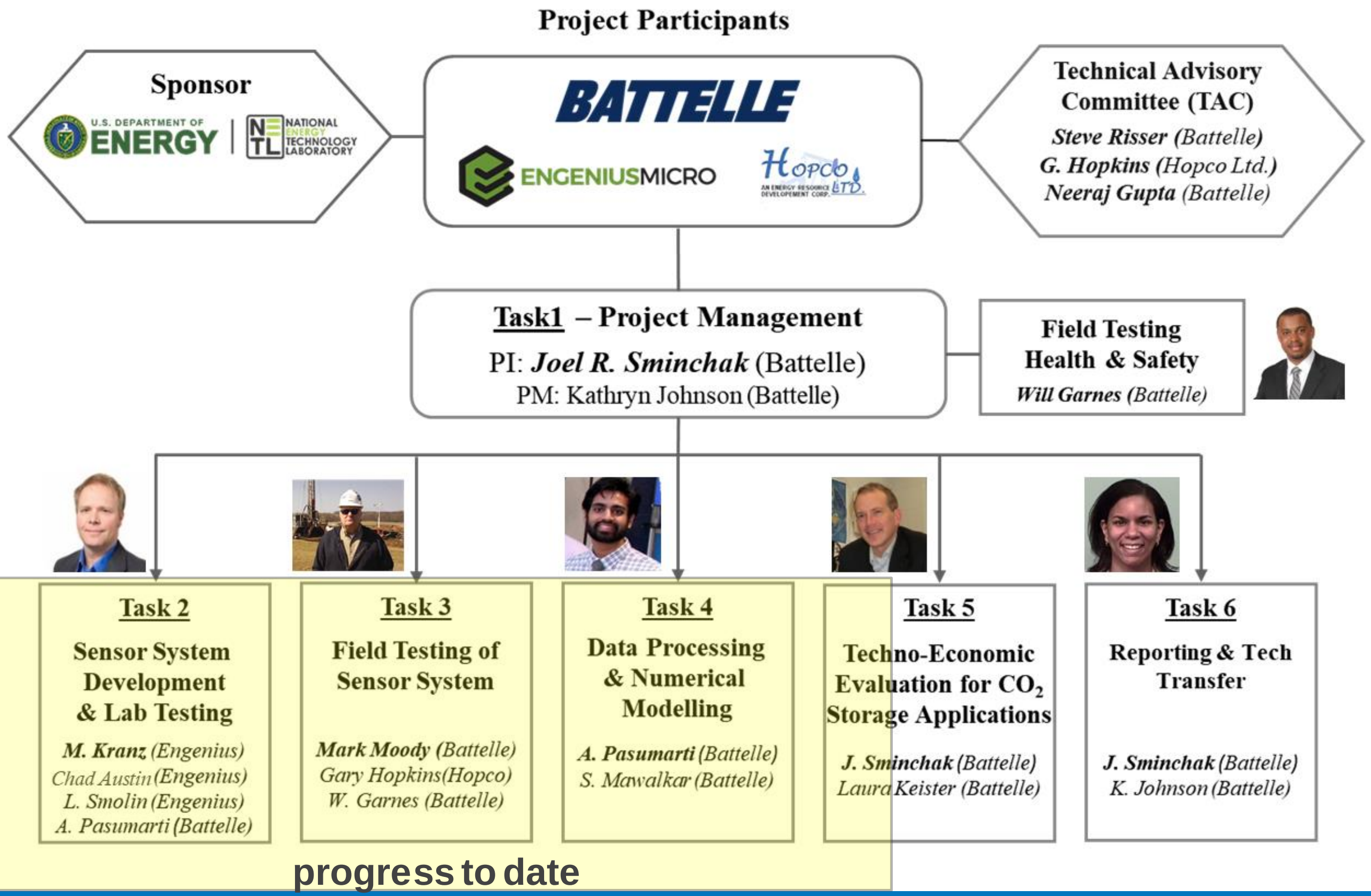
Technical Status

- The project is organized into 5 main technical tasks.
- Field testing task completed Oct-Nov 2022.



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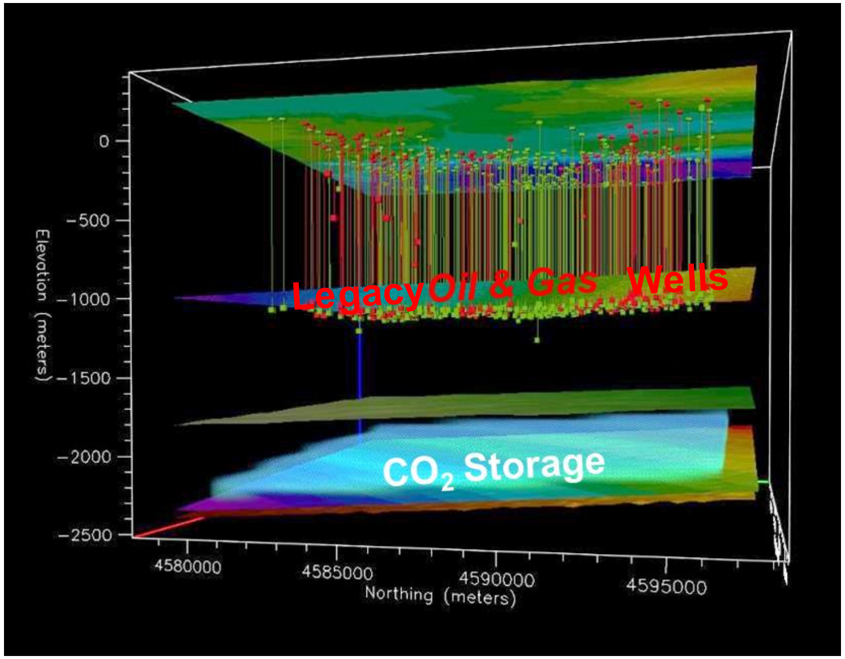
Technical Status

- Objective = Develop wireless microsensors system for emplacement in CO_2 storage or legacy oil & gas wells to monitor temperature as proxy for CO_2.

Legacy oil & gas wells may be used for monitoring CO_2 storage



Temperature as CO_2 Indicator

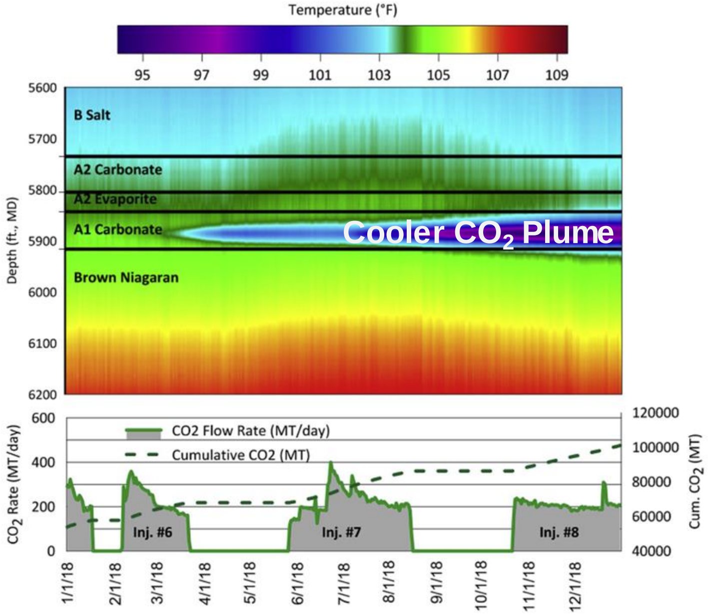
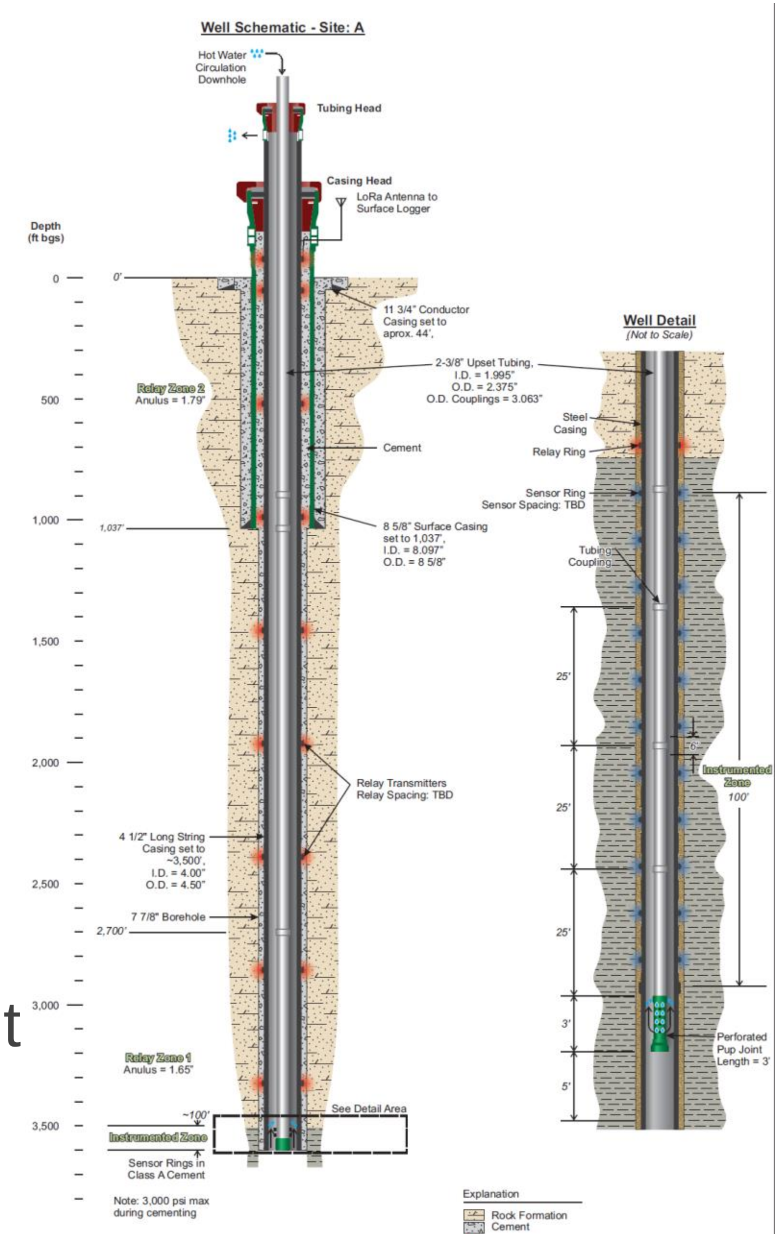


Fig. 8. Plot of depth vs. temperature at Chester #8-16 monitoring well.

Technical Status

- ‘Sensor ring’ concept was adopted to facilitate system development:
  - wireless microsensors,
  - encapsulation for downhole CO_2 conditions,
  - central data collection & transmitter,
  - wireless charging & energy harvesting options,
  - data relay system to surface,
  - retrievable wireless battery charging.
- Early-stage proof of concept platform, many different deployment options (“sensor balls”) if successful.



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Testing Timeline

1. Lab scale testing of sensors.

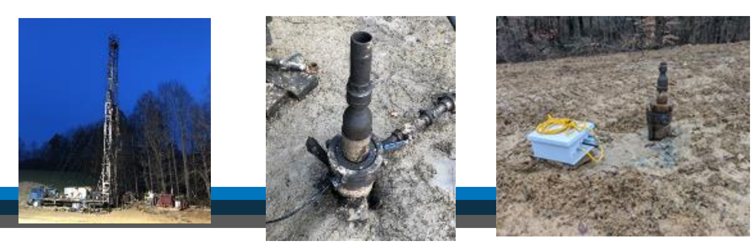
2. Bench-scale testing of data relay ring in a series of test pipes constructed in lengths of 3’, 9’, 27’, and 120’.

3. Warehouse testing of sensor rings/relays with potting compound and installed on 4 ½” casing.

4. Field testing on Dennis #1 well to 2500 ft cemented to surface.

5. Field testing on Hickenbottom #1 to 1153 ft before cement job 0-250 ft zone.

6. Cement Hickenbottom #1 well to surface for long-term testing.



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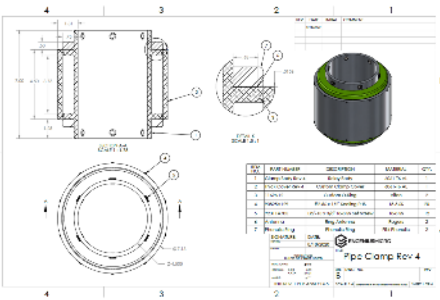
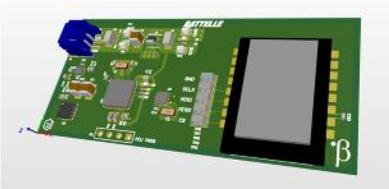
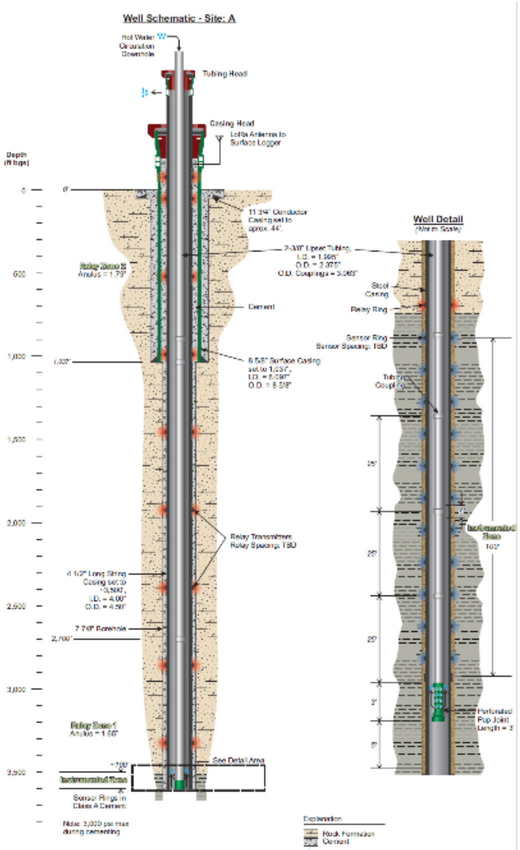
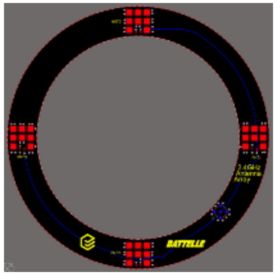
Sensor Design

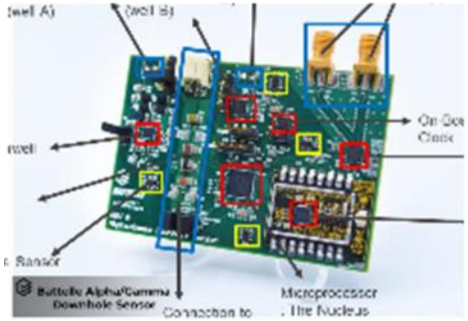
- Sensor system design completed in Dec. 2020 (*Sensor Design Memo*).
- Sensor “ring” approach was adopted to facilitate wireless RF data transmission up well <u>through oilfield cement</u>, wireless power, & installation in legacy O&G wells.

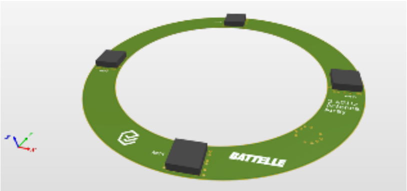








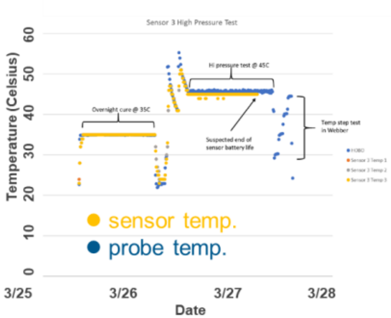




Technical Status: Lab, Bench Tests

- A sensor prototype & housing was exposed to supercritical CO_2 in a pressure test cell at temperatures ranging from 20 °C to 50 °C and pressures up to 1,400 psi for 24 hrs.
- Data relay ring communication testing through cement was completed in a series of test pipes constructed in lengths of 3’, 9’, 27’, and 120’.

Lab Exposure Supercritical CO2 Tests



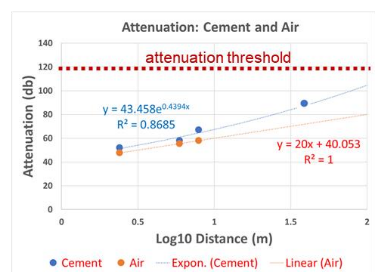
Before

Top: before CO_2 exposure testing.

Bottom: after CO_2 exposure testing.

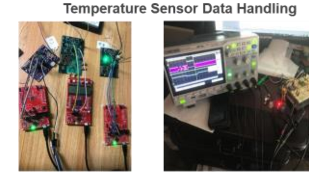
After

Bench Scale Tests of Sensors



Functional Demos

Temperature Sensor Data Handling



Field Testing Objectives

- Install wireless sensor system in two legacy oil and gas wells.
- Demonstrate that the individual components and wireless sensor system can function in downhole conditions by monitoring downhole temperature in 100 ft instrumented zone and wirelessly transmit data to surface.

Item	Objectives
Site preparation and well work	- Prepare the two test wells for field activities.
Microsensor System Installation	- Install sensor system in test wells. - Develop/demonstrate a practical deployment methodology suited to real-world application in wellbore applications.
Sensor System Field Testing in Well #1	- Demonstrate that wireless data telemetry through annular cement is feasible. - Demonstrate survivability and functioning of all designed components in the downhole environment both during deployment and after. - Determine the greatest distance through the annular cement through which RF communication can occur. - Complete initial 2-3 day validation test of sensor system in test well #1 at subsurface conditions similar to CO_2 storage sites.
Sensor System Field Testing in Well #2	- Complete 2-3 month test of sensor system in test well #2 at subsurface conditions similar to CO2 storage sites to confirm CO_2 monitoring capabilities. - Demonstrate energy harvesting in downhole environment via inductive charging.
Field demobilization and site closure	- Close out site and turn over to operator.

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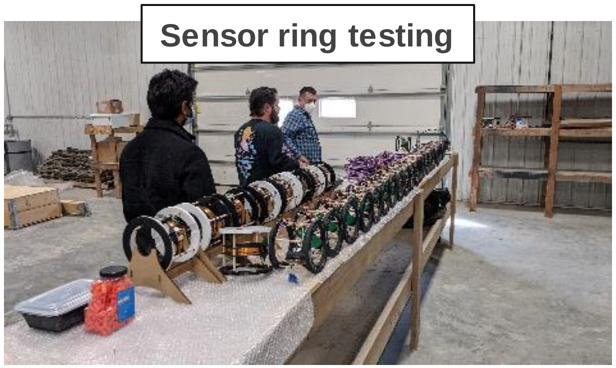
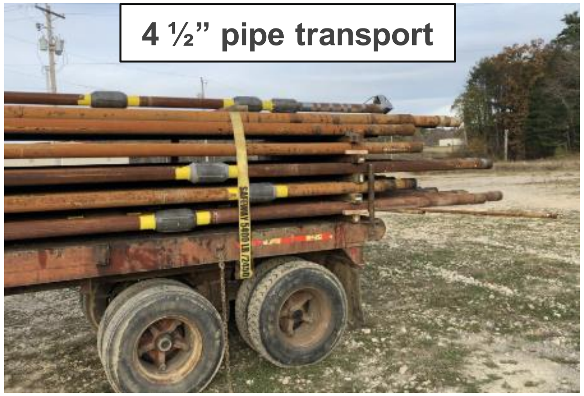
Warehouse Staging of Sensor System

- Sensor rings installed on 4 ½” casing in a warehouse in Cambridge, OH.
- Composite centralizer clamped over sensor rings to protect electronics.
- Sensor system function verified along with wireless powering.





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Dennis #1 Well Testing

- Well workover preparation completed in Dennis #1 well to squeeze Clinton Ss perforations (5140-5200') and allow sensor system installation.
- Sensor rings run on 4 ½" casing to 2500 ft. Sensor relays set at 40-80 ft spacing (except 100-200 ft spacing from 2000-2500 ft).
- Well cemented to surface in 2-stage job and CBL run to confirm cement.

Running 4 ½" casing with Sensor Rings in Dennis #1 Well

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Dennis #1 Well Testing

- Sensor system testing did not post data from top sensor to data logger.
- Top 10 ft of well was excavated for root cause analysis, which showed sensor ring was working but not communicating via cable.
- Possible damage of the top sensor ring cable to surface antenna, software issues, and antennae orientation.

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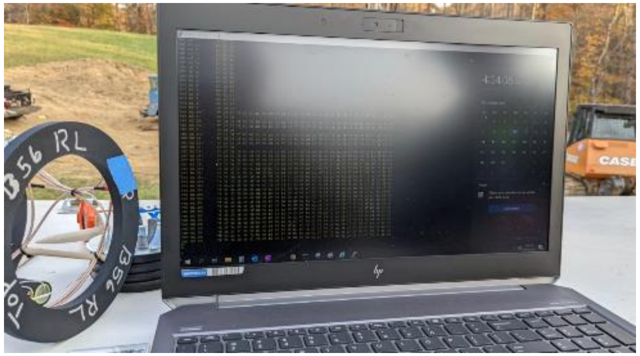
Hickenbottom #1 Well Testing

- Hickenbottom #1 well was squeezed off in Clinton Ss (5117-5181’) and cement plug was set at 3867 ft to facilitate sensor ring installation.
- Sensor system configuration was adjusted to 10-40 ft relay spacing to a depth of 1154 ft in the Hickenbottom #1 well.
- Sensor rings run on 4 ½” casing to 1154 ft.

Running 4 ½” casing with Sensor Rings Hickenbottom #1 Well

Hickenbottom #1 Well Testing

- Sensor system posts temperature data to depth of 250 ft after installation.
- Water deeper than 250 ft appears to block data transmission.



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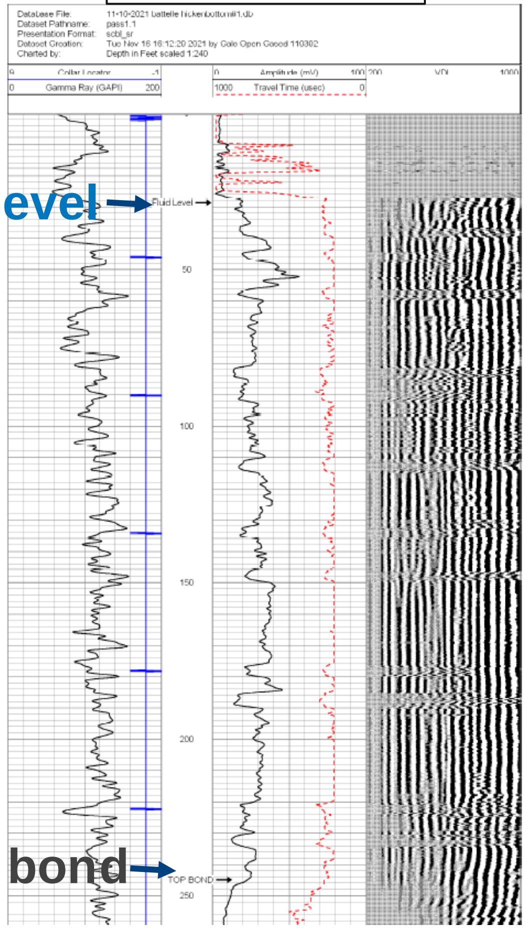
Hickenbottom #1 Well Testing

- Well cemented from 3788 ft to surface in 2-stage job.
- Data transmits to only 3 sensor rings.
- CBL shows top of cement at ~246 ft and water in well blocking RF signal.

Cement Bond Log



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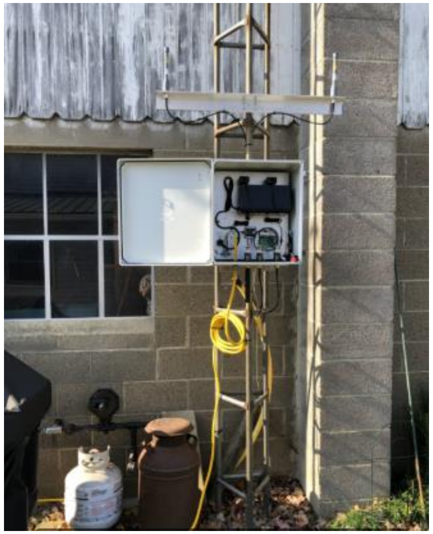
Hickenbottom #1 Well Testing

- The well was perforated at 240-250 ft to drain water out the annulus and a cement job completed 11/16/2021 to cement off top 250 ft to surface.
- Temperature sensor system monitored but no signal beyond cabled sensor ring until 12/29/21 when next wireless ring posts temp data.
- System ops monitored 1/16/22 with same results -99 dB RSSI one hop.

Data logger/Transmitter

Testing Sensor System



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Summary Timeline

- Sensor system tested over 4 months in Dennis #1 and Hickenbottom #1.

Dennis #1 (API# 34-2-0590-23337, Guernsey Co., OH, TD 5335 ft, 8/17/1982)				
Date	**Test**	**Staff**	**Summary**	**Results**
10/1/2021	Well workover	Moody	Start well workover to squeeze Rose Run production and cement well	Start rework to cement off production zone in well
10/21/2021	Well preparation	Moody	Prepare well for sensor system installation	Complete squeeze job, set cement plug, run CBL and logs
10/14/2021	Sensor system install	Lanham, Moody, Place, Pasumarti	Install sensor system to 2500 ft	Run sensor system to 2500 ft on 4 1/2" casing
10/14/2021-10/21/2021	Sensor system function	Lanham, Pasumarti	Test sensor system function after cementing 4 1/2" casing 0-2500 ft	No signal from wellhead sensor relay ring or deeper sensor rings
10/22/2021	Sensor system function	Moody, Lanham, Pasumarti	Excavate 8 ft around wellhead, cut well off to retrieve cabled sensor ring	Wireless signal from wellhead sensor relay ring but no signal from wired connection, no signal from deeper sensor rings in cemented annulus
10/22/2021	Well P&A	Moody/Place	Complete well plugging & abandonment, reclaim site	Well P&A complete

Hickenbottom #1 (API# 34-2-0590-22746, Guernsey Co., OH, TD 5242 ft, 7/17/1980)				
Date	**Test**	**Staff**	**Summary**	**Results**
11/3/2021	Well workover	Moody	Start well workover to squeeze Rose Run production and cement well	Start rework to cement off production zone in well
11/9/2021	Well preparation	Moody	Prepare well for sensor system installation	Complete squeeze job, set cement plug, run CBL and logs
11/10/2021	Sensor system install	Lanham, Moody, Place, Sminchak	Install sensor system to 1154 ft	Run sensor system to 1154 ft on 4 1/2" casing
11/10/2021	Sensor system function	Lanham, Moody, Place, Sminchak	Test sensor downhole function after 4 1/2" casing installation	Sensor system functions to 250 ft depth, water in well appears to prevent function deeper than 250 ft
11/15/2021	Sensor system operations	Lanham, Moody	Test sensor system after cementing 4 1/2" casing 250-1154 ft	Top three sensors work, no data deeper due to water in well
11/18/2021-11/22/2021	Sensor system operations	Place, Moody	Test sensor downhole function after 4 1/2" casing cement job	Sensor system functions to 231 ft depth, water in well appears to prevent function deeper than 250 ft
12/2/2021	Sensor system function	Place	Test sensor downhole function after cementing 0-250 ft 4 1/2" casing	No data beyond 1st sensor relay
12/17/2021	Sensor system operation	Sminchak, Moody	Test sensor system downhole function with particle box	No data beyond 1st sensor relay
12/29/2021	Sensor system operations	Sminchak	Test sensor system downhole function with particle box	Data transmission to 2nd relay @ 99 dB RSSI
1/12/2022	Sensor system operations	Sminchak	Test sensor system downhole function with particle box	Data transmission to 2nd relay @ 98 dB RSSI
2/2/2022	Sensor system operations	Sminchak	Test sensor system downhole function with particle box	Data transmission to 2nd relay @ 98 dB RSSI
3/11/2022	Sensor system operations	Sminchak	Test sensor system downhole function with particle box	Data transmission to 2nd relay @ 98 dB RSSI
Summer 2022	Well P&A	Moody/Place	Complete well plugging & abandonment, reclaim site	Well P&A complete

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Sensor System Field Testing Results

Successes

- Installation of the sensor system demonstrated capability for CCS monitoring using legacy oil & gas wells. The field service companies were able to run the sensor ring centralizers and relays on 4 ½" casing into well, cement the well, and complete well work.
- Temperature sensor rings functioned in downhole environment.
- Automated remote data collection (via particle boron system) relayed sensing data to the cloud.
- Wireless powering demonstration for long-term deployment of sensors.

Challenges

- Wireless transmission in downhole environment
- Durability of electronic components.
- Reliability of the sensor components.
- Reducing water in portions of the well. Water in the casing annulus blocked RF transmission. Therefore, it was important to eliminate water in uncemented zones of the casing annulus.

Technology Features

Feature	Demonstrated?	Notes
Wireless communication in a downhole annular environment, esp. upper portion of well.	Yes	Communication demonstrated in the surface casing region (pipe-in-pipe). Presence of water is destructive to communication. Cementing reduced range.
Cloud-based, real-time data retrieval and storage	Yes	Complex and multi-layered software system, that needed field-scale testing to iron out kinks.
Energy harvesting for temperature sensing	Yes.	Demonstrated with fiber-glass tubing in the warehouse. Needs demo at field-scale.
Environmental survivability and deployment protocols	Yes	Smart centralizer is very robust. Steep learning curve for deployment in the field. Protocol fine-tuned with each successive well.
Wireless transmission range >40ft (more than 1 casing joint)	No	Field-scale testing did not reflect bench-scale testing. More testing with advanced cementing materials needed.
Integrated system: Sensing, Relay and Data Logging	Yes	Sub-systems demonstrated at both bench and field scale. Transmission range must be extended for full testing.

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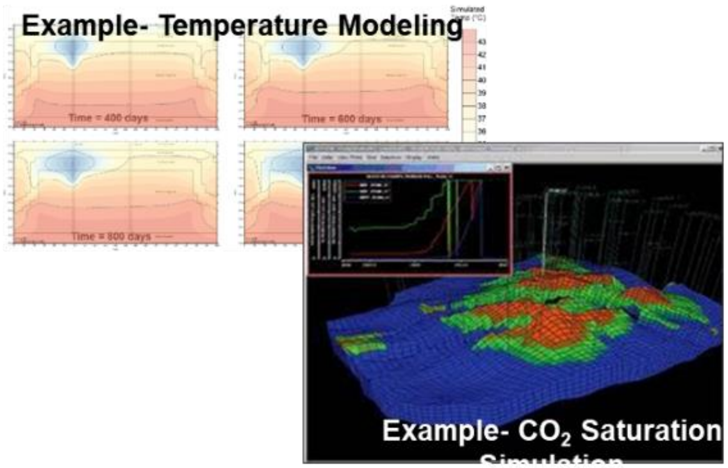
Sensor System Field Testing Results

Path Forward

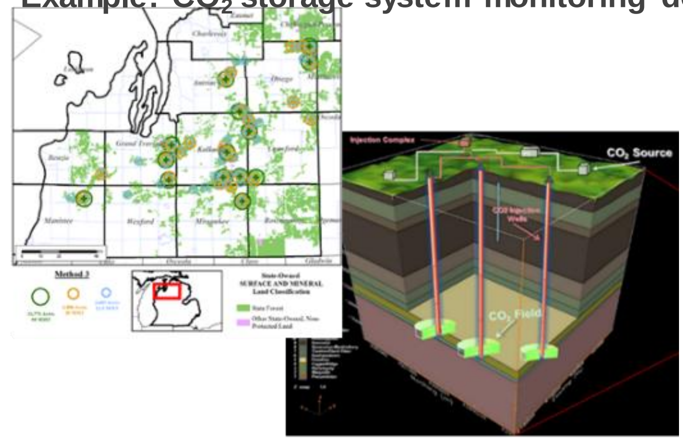
- Continue to monitor sensor system in Hickenbottom #1.
- RF transmission enhancement & bench scale tests.
- Increase durability of sensor components.
- Extend battery life.
- Explore additional applications.
- Improve software functionality.
- Miniaturize sensor components for sensor ball type applications.

Data Processing/Modeling & Techno-Economic Evaluation

- Data Processing and Numerical Modelling
  - Data processing and QA/QC
  - Numerical modeling of field microsensor data
  - Verify CO_2 plume w/temperature
- Techno-Economic Evaluation for CO_2 Storage Applications
  - Assessment of monitoring integration with existing technologies
  - Benchmarking analysis of microsensor system applications



Example: CO_2 storage system monitoring design



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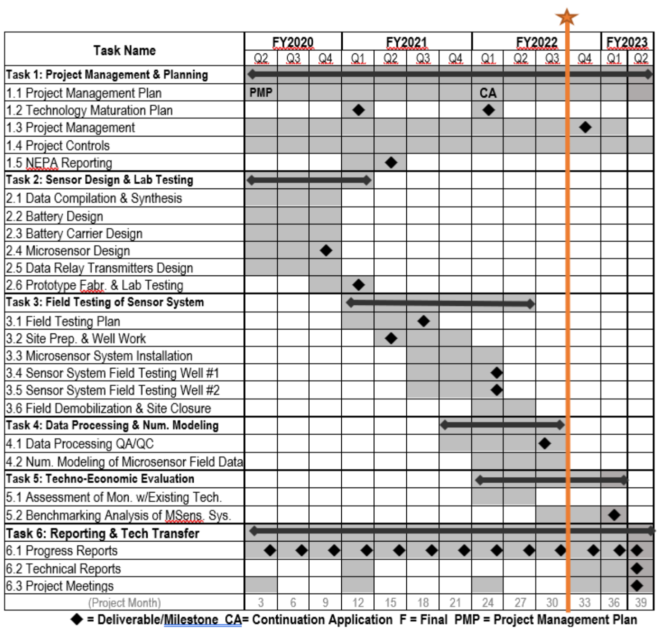
Accomplishments to Date

- Sensor design and lab testing completed for wellbore telemetry, temperature monitoring, wireless charging, energy harvesting, data transfer, and field tests.
- Field testing completed for September-October 2021 in 2 existing oil wells in Guernsey Co., Ohio.

Schedule



Milestones

Task/ subtask	Milestone Title & Description	Completion date	Verification method
1.1	Update project Management Plan	**February 12, 2020**	Electronic Document Submission
2.5, 2.6	Microsensor System Design	**December 2020**	Sensor Design Memo
2	**Decision Point to Move to Field Testing**	**February 2021**	**DOE-NETL Approval**
2.6	**Complete Field Test Unit Construction**	**March 2021**	**Sensor System Lab Test Memo**
3.0	**Confirm wells for field testing**	**January 2021**	**Final NEPA Env. Quest.**
3.1	**Prepare Field Testing Plan (sensor system deployment plan complete)**	**May 2021**	**Field Testing Plan Submitted Electronically**
3	**Decision Point on Final Field Sites**	**February 2021**	**DOE-NETL Approval**
3.6	**Sensor Data Collection (sensor data successfully collected)**	**February 2022**	**Field Testing Summary Report Submitted Electronically**
4.3	Sensor Data Validation (data validated by numerical simulations)	June 2022	Field Data Submitted Electronically to EDX
5.1	Technology Development Plan (techno-economic assessment and methods)	October 2022	Technology Development Plan Submitted Electronically
6.3	Complete Project and Final Report (final DOE submittal)	January 2023	Final Report Submitted Electronically

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Lessons Learned

- The project team successfully demonstrated sensor system operation at supercritical conditions lab testing, 120 ft cemented casing data transmission test on surface, and functional bench-scale demos.
- Field testing completed in two oil wells at depths of 2500 ft and 1153 ft.
- A sensor ring approach was adopted to allow for functional technology field testing, accommodate legacy well specifications, and explore data transmission lengths, effect of well materials on data signals, energy harvesting options, wireless charging, and data handling.

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Project Summary

- Three-prong project approach: 1) develop a wireless downhole sensor system to monitor for CO_2 storage, 2) field test the sensor system in two legacy oil & gas wells, and 3) validate the technology and demonstrate its applicability to monitoring CO_2 in the subsurface.
- Key advancements in generated through this research: distributed wireless microsensor system, wireless telemetry system to transmit data to surface, customized deployment options, and an approach to processing and integrating sensor data to understand CO_2 distribution and track CO_2 plume movement in the subsurface.
- Path Forward
  - Data Analysis, Modeling, & Techno-Economic Evaluation
    - Assess options for improving wireless communication (polymer cement, low frequency)
    - Model CO_2 temperature indicator for CO_2 storage
    - Techno- economic deployment options for legacy O&G wells, CO_2 wells

Appendix Material

- As follows

Benefit to the Program

- Project addresses FOA1998 Area of Interest 1: *Transformational Sensing System for Monitoring the Deep Subsurface:*
- **Wireless microsensors system for CO_2 storage applications**.
- System deployment options for legacy oil & gas wells.
- Network of real-time monitoring points for CO_2 storage zones without the expense of new wells.
- Real time, autonomous monitoring data for accurately tracking/modelling the subsurface movement of CO_2 plumes.
- The sensor system benefits operators, regulators, and stakeholders associated with diverse CO_2 storage applications:
  - Commercial-scale deep saline CO_2 storage sites,
  - CO_2-EOR operations/optimization,
  - 45Q monitoring/reporting/verification requirements, and
  - USEPA Class 6 UIC requirements for geologic CO_2 storage.

Project Overview- Goals and Objectives

- Three-year project under DOE-NETL FOA1988 (Feb. 2019-Apr. 2023).
- Project participants: Battelle (lead), EngeniusMicro, HOPCO LTD.
- Project budget: Govt. Share: $2,374,747 Cost Share : $677,000
  Total : $3,051,747

The goal of this project is to develop a technology for wireless downhole monitoring subsurface operations via a three-prong approach:

1. **Sensor System Development**- design and fabricate a fully integrated wireless microsensor-based downhole sensing system to measure temperature as the primary indicator of CO_2 presence.
2. **Field Deployment/Demonstration**- demonstrate system operational feasibility by deploying & testing the system in the casing annulus of two legacy 5000-6000 ft boreholes.
3. **Techno-Economic Analysis**- establish the technical feasibility and practical utility of the sensing system for reservoir and above zone monitoring in a commercial-scale CO_2 storage complex.

Project Organization Chart

Project Participants

Sponsor

U.S. DEPARTMENT OF ENERGY | NATIONAL ENERGY TECHNOLOGY LABORATORY

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ENGENIUSMICRO

Hopco LTD. AN ENERGY RESOURCE DEVELOPEMENT CORP.

Technical Advisory Committee (TAC)

Steve Risser *(Battelle)*
G. Hopkins *(Hopco Ltd.)*
Neeraj Gupta *(Battelle)*

Task1 – Project Management

PI: ***Joel R. Sminchak*** (Battelle)
PM: Kathryn Johnson (Battelle)

Field Testing Health & Safety

Will Garnes *(Battelle)*

Task 2

Sensor System Development & Lab Testing

Chad Austin (Engenius)
M. Kranz (Engenius)
B. English (Engenius)
A. Pasumarti (Battelle)

Task 3

Field Testing of Sensor System

Mark Moody *(Battelle)*
Gary Hopkins(Hopco)
W. Garnes (Battelle)

Task 4

Data Processing & Numerical Modelling

A. Pasumarti *(Battelle)*
S. Mawalkar (Battelle)

Task 5

Techno-Economic Evaluation for CO_2 Storage Applications

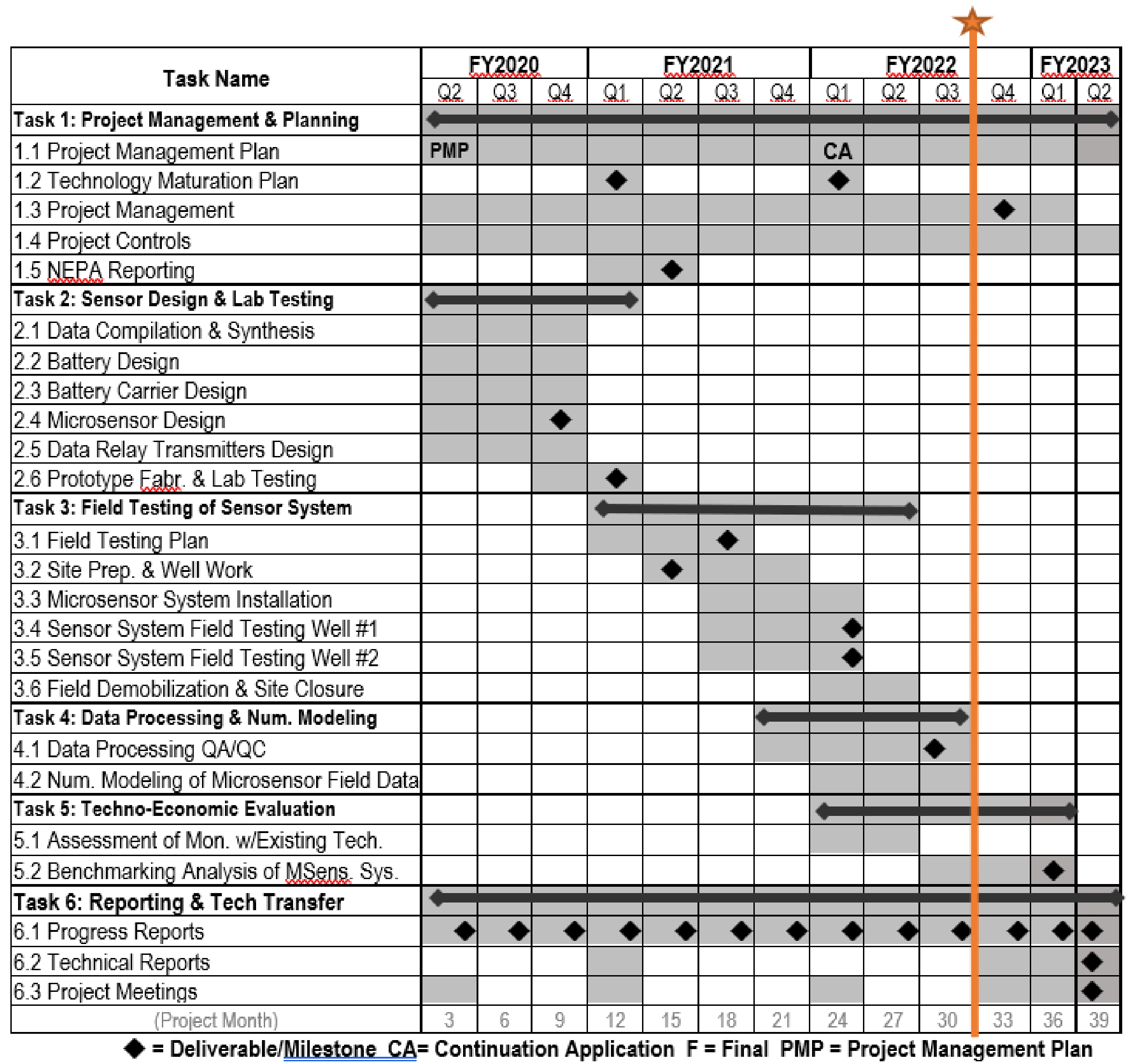
J. Sminchak *(Battelle)*
Laura Keister (Battelle)

Task 6

Reporting & Tech Transfer

J. Sminchak *(Battelle)*
K. Johnson (Battelle)

Gantt Chart


Task Name
FY2020
FY2021
FY2022
FY2023
Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2
Task 1: Project Management & Planning
1.1 Project Management Plan
PMP
CA
1.2 Technology Maturation Plan
1.3 Project Management
1.4 Project Controls
1.5 NEPA Reporting
Task 2: Sensor Design & Lab Testing
2.1 Data Compilation & Synthesis
2.2 Battery Design
2.3 Battery Carrier Design
2.4 Microsensor Design
2.5 Data Relay Transmitters Design
2.6 Prototype Fabr. & Lab Testing
Task 3: Field Testing of Sensor System
3.1 Field Testing Plan
3.2 Site Prep. & Well Work
3.3 Microsensor System Installation
3.4 Sensor System Field Testing Well #1
3.5 Sensor System Field Testing Well #2
3.6 Field Demobilization & Site Closure
Task 4: Data Processing & Num. Modeling
4.1 Data Processing QA/QC
4.2 Num. Modeling of Microsensor Field Data
Task 5: Techno-Economic Evaluation
5.1 Assessment of Mon. w/Existing Tech.
5.2 Benchmarking Analysis of MSens. Sys.
Task 6: Reporting & Tech Transfer
6.1 Progress Reports
6.2 Technical Reports
6.3 Project Meetings
(Project Month)
3 6 9 12 15 18 21 24 27 30 33 36 39
◆ = Deliverable/Milestone CA= Continuation Application F = Final PMP = Project Management Plan